Evaluation of a Novel Active Exoskeleton for Tasks at or Above Head Level

Bernward M. Otten, Robert Weidner, and Andreas Argubi-Wollesen

***Abstract*—Tasks at or above head level have been known to cause discomfort and musculoskeletal disorders. This letter presents a novel wearable active pneumatic exoskeletal support system with a power tool based control interface to make work at head level or above more comfortable. Subjective task effort (Borg CR10), movement velocities, and muscle activity (surface electromyography) have been evaluated and different passive and active operation modes are being compared. We show that the exoskeleton is capable of performing a substantial reduction in muscle activity, increasing upper arm elevation velocities, and reducing task effort. The comparison of an active support mode with a trigger button at the tool grip with a passive support mode showed that users reported less resistance for lowering the arm and increased velocities when they were able to adjust the support with a simple button. We show that for tasks with a varying weight of loads, an adaptive active exoskeleton is greatly beneficial over a passive one as it eases usability and acceptance.**

***Index Terms*—Manufacturing, exoskeletons, support system, human augmentation, human computer interface, human hybrid robot.**

I. Introduction

INTENSIVE effort of researchers from various fields has allowed to improve workplace ergonomics or automate strenuous tasks. Despite this effort, many strenuous workplaces remained part of the production landscape. Furthermore, reported levels of exposure to some physical risks (esp. "tiring and painful positions" and "repetitive hand or arm movements") have seen an increase from 1991 throughout 2012 [1]. It is known that tiring positions, repetitive movements, and handling heavy objects (e.g., tools and components) are linked with work related musculoskeletal diseases (wMSDs) [2].

Whereas novel technological approaches such as human-robot-collaboration will allow for productivity and ergonomic improvements, the human is expected to remain an essential part in the industrial production for the foreseeable future [3]. From a control perspective, manipulated objects often have different weights and in manufacturing there is frequent change between main tasks and side tasks, hampering the effectiveness of simple control schemes.

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Multiple studies [2], [5], [6] have identified a relationship between work at head level and above as well as musculoskeletal diseases. As this is known since decades, effort has been made to reduce the necessary work in such positions.

However, it is still an essential part of many workplaces in industry (most notably automotive and aerospace) and construction.

II. Design and Development of the Exoskeleton Lucy

There have been several industrial exoskeletons targeting tasks at head level or above using various technical approaches [7]–[9]. Three main aspects can be identified when comparing different exoskeleton concepts:

- Path of force: path along which the force is transferred by the technical systems around body parts or regions (anthropomorphic vs. non-anthropomorphic designs).
- Rigidity of the structural elements: soft textile approaches [10], [11] vs. rigid exoskeletal approaches [8].
- Type of actuation: active vs. passive actuation as well as number of supported degrees of freedom (DOF).

Exoskeletons in the past have been utilizing non-anthropomorphic [9] as well as anthropomorphic designs [8]. In research there is a wide range between full-body exoskeletons and specialized exoskeletons for certain parts of the body. Most recent commercial industrial exoskeletons like the "Laevo" (Laevo B.V., Delft, NL), the "suitX" (US Bionics Inc., Berkeley, USA) as well as the "Levitate Airframe" (Levitate Technologies Inc., San Diego, USA) make use of rigid structural elements close to the body and rely on passive actuation of single DOFs. There is also an increasing number of soft passive and active exoskeleton suits [10], [11].

Whereas most commercially available exoskeletons rely on passive actuation, there are numerous active industrial exoskeletons in research. Many using electric actuation on multiple DOFs [8], however there are also pneumatic designs. One approach with pneumatic actuators is described in [12] – the support system called "Lucy".

The most recent work of Lucy intents to follow a hybrid approach in the domains of actuation as well as structural rigidity by integrating soft and rigid structural elements close to the body and combining passive and active actuation characteristics.

A. Previous Work on Lucy

The support system Lucy is a result of intensive research efforts exploring several approaches targeting industrial assistance [13]. The line of development towards the most recent system can be seen in Fig. 1. The first approach (called Jonny) is based on a commercially available camera balancing system (Steadicam), which was equipped with a tool mount to hold

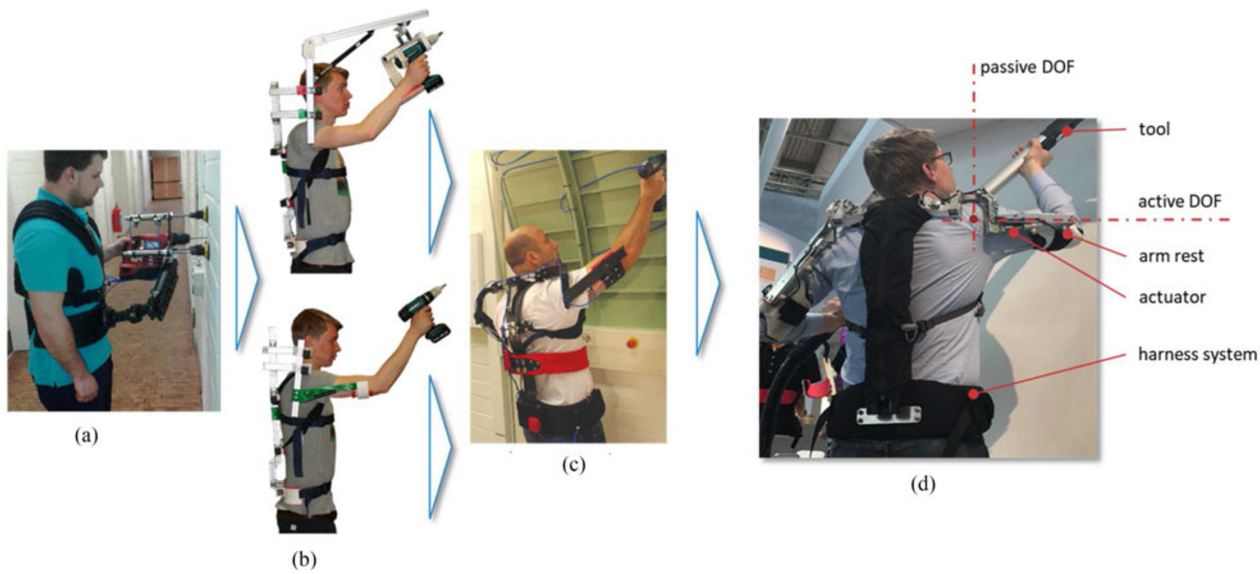

Fig. 1. Predecessors of the exoskeleton Lucy 2.0. Previous approaches compared different force paths further away from the body and close to the body. Force paths close to the body showed superior results. (a) Third arm support system Jonny with rigid abdomen structure [14]. (b) First prototypes of crane and arm support with rigid back structure [15]. (c) Support system Lucy 1.0 with flexible back structure [12]. (d) Optimized support system Lucy 2.0.

heavy tools and transfer the load to the breast/abdomen [14]. This approach was limited in its range of motion as wells as practicability. Therefore a custom harness with a rigid back structure was designed and two different kinematic linkages (a crane type linkage with a force path above the head and a more anthropomorphic one with a force path close to the body) have been developed (see Fig. 1(b)) for this harness. These two approaches have been extensively compared in a study using 3D motion analysis, ground reaction forces and electromyography [15].

The results of the study showed, that both approaches were capable of performing a significant reduction in muscle activity. Moreover, the results underlined the practical benefits of a force path close to the body. The experience with this prototypes [16] has shown, that a flexible back structure can allow more uninhibited movements. Therefore, a flexible exoskeletal structure was introduced to the design with Lucy 1.0 [12]. The force path of Lucy 1.0 runs along the upper arm and along the back, transferring parts of the tool weight and the arm weight to the pelvis (see Fig 1(c)).

The exoskeleton Lucy 1.0 comprises one active DOF on each side for the elevation of the upper arm. For actuation, pneumatic cylinders were used, but they could be replaced with a gas spring for passive operation. Whereas passive actuation seemed practical at first, being able to adjust the pressure and switch the system off easily, when no assistance is desired, was named as a key feature by test subjects in various industrial settings. This was the motivation to further investigate a pneumatic control system, which can adjust the pneumatic pressure in the cylinders and react to various input devices as presented here.

B. Addressing Shoulder Biomechanics

The shoulder girdle is a rather complex musculoskeletal area in the human body. The glenohumeral joint comprises three rotational degrees of freedom and in conjunction with the sternoclavicular joint and the scapulocostal joint, the shoulder girdle contains three additional translational degrees of freedom. Therefore, alignment between any exoskeletal system and the human body is difficult to realize as during upper limb movement, the functional rotation axes of the glenohumeral joint constantly shifts on the translational trajectories [17].

The mismatch between both systems creates an additional torque towards the joint, which can cause discomfort or lead to injury. Lucy 2.0 has been created with respect to this challenge. Matching between subject and system is based on the proper alignment at the shoulder at rest (0° anteversion of the arm). During upward motion of the arm, the joint center of the system changes according to the glenohumeral joint´s general translational movement whilst allowing the shoulder to move freely along the translational axes.

C. New Design Features of Lucy 2.0

Fig. 1(d) highlights the passive and active degrees of freedoms (DOFs) of Lucy 2.0. In order to regulate the pressure in the pneumatic cylinders supporting the upper arm, a custom pressure control unit was developed using solenoid valves and a pressure sensor. Whereas one solenoid valve is configured to let pressurized air from the supply to the actuator to increase pressure, a second is configured to let air out of the actuator to the environment.

A simple control scheme is executed on a microcontroller opening the inlet valve, when the desired pressure is above the currently measured pressure and opening the outlet valve when the pressure in the actuator needs to be reduced. This setup was chosen due to its advantages in weight and space over conventional proportional valves and because it provides full control over the amount of air being used.

III. Exoskeleton Control Structure

Industrial exoskeletons often work by providing additional torque to human joints. Therefore, it is not sufficient to have a control scheme minimizing interaction forces. Rather it is necessary to provide sufficient interaction forces at the right time [4]. For research exoskeletons [18] and medical exoskeletons [19] this challenge has been approached by measuring muscle activity through surface electromyography and using this signal as a basis for the necessary support torque. As (surface) electromyography is facing several drawbacks such as practicability and varying results it is currently not feasible for industrial exoskeletons. Consequently, it is necessary to have a profound understanding of the tasks the exoskeletons will be used for and estimate user intention [4].

Some passive exoskeletons have shown, that for simple tasks, setups with mechanically fixed relationships between actuator angle and actuator torque are sufficient. For many tasks and applications however, especially when the load is varying greatly, it is necessary to adapt the level of support during work processes [4].

Due to an iterative and participatory development approach [13], the support system Lucy is continuously evaluated. In general, users have reported a substantial lifting aid. However, there was a large variation in the perceived support. Aspects challenging in terms of control proofed to be tasks with varying levels of load of the manipulated objects, as force aid was either too strong without load or too low with a heavy object picked up. Also, tasks where objects had to be picked up from a position that required the user to lean down forward and stretch the arms down, were challenging as the exoskeleton pushed the arms up against the user's intention. In general, exoskeletons should be adapted to different work scenarios. This requires the exoskeleton not only to respect the state of the body parts supported and the overall level of support but also discriminate between different sub-tasks.

Therefore we propose a novel tool based interface, which in the first iteration is equipped with a button at the grip of the tools being used (Fig. 4), allowing the user to increase the support during task execution. This solution overcomes some of the limitations of passive exoskeletons (which either do not allow changing support torque at all or only prior to task execution), without becoming substantially more complex. With the proposed solution users can reduce support torque, when lowering the arm or they do not use the (heavy) tool.

The active (pneumatic) actuation, necessary for these active control schemes, however, comes at the cost of a more complex actuation system (compared to passive actuation) and necessitates an evaluation if the additional effort is justified.

A. Mechanical Characteristic of Actuator

"Lucy" has two different ways to adapt the torque for supporting upper extremities at the active shoulder joint: It is possible to adapt the technically possible torque or alter the support torque by software. The technically possible torque τ is generated by a pneumatic cylinder in the upper arm link (see Figs. 1(d) and 2). The active degree of freedom of Lucy creates a torque τ

$$\tau = A_{\text{cyl}} \cdot p_{\text{cyl}} \cdot \sin\left(\frac{d \cdot \sin(\alpha)}{\sqrt{d^2 + l^2 - 2ld \cdot \cos(\alpha)}}\right) \quad (1)$$

with:

- A_{cyl} cylinder surface area in mm^2,
- p_{cyl} air pressure inside cylinder in $\text{N}\cdot\text{m}^{-2}$,
- d length upper arm bar in mm, as well as
- L lever arm length in mm.

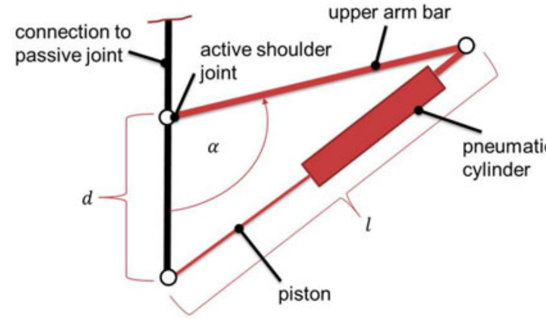

Fig. 2. Kinematic linkage of pneumatic cylinder and upper arm bar, the effective lever arm increases with upper arm elevation α.

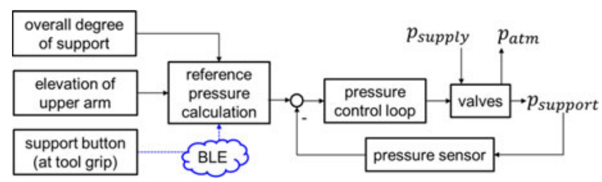

Fig. 3. Three types of information used to calculate the desired cylinder pressure: (a) overall degree of support adjusted by rotary knob, (b) button at tool grip for additional support or (c) linear potentiometer to adjust pressure depending on upper arm elevation. Tool is connected wirelessly over Bluetooth low energy (BLE).

at the shoulder joint, which is defined by the used actuator and kinematics. The effective lever arm increases with upper arm elevation α. Thus torque changes over the range of motion. The maximum torque is reached when the upper arm is almost horizontal (see Fig. 6). Within this maximum torque envelope, support torque can be regulated by reducing the pressure in the pneumatic cylinder.

B. Calculation of Reference Pressure

Currently the calculation of the target pressure for the pneumatic cylinder is based on three types of information: a) elevation angle of the upper arm measured with a flat linear potentiometer, b) individual (over-all) support force preference given by a rotary knob mounted to the shoulder strap, or c) by a remote push button (see Fig. 3) located at the grip of the tool being used. The tool is connected to the exoskeleton via Bluetooth Low Energy (BLE).

After a specific elevation angle in shoulder flexion, the physiologically available muscle torque provided by the shoulder complex is decreasing [20]. Therefore increasing the torque when the arm is elevated is the primary objective. Furthermore, users do not want to be pushed up by the system, when the upper arm is close to the body. Consequently, the reference pressure $p_{s_{\text{ref}}}$, which sets the target for the low-level pressure control loop (see Fig. 4 for an overview of the control structure), is defined as

$$p_{s_{\text{ref}}} = \frac{\alpha - \alpha_{\text{start}}}{\alpha_{\text{end}} - \alpha_{\text{start}}}\, p_{\text{elevated}} \quad (2)$$

with:

- p_{sref} reference pressure in bar,
- α_{start} start angle of support in degree,
- α_{end} end angle of support in degree, as well as
- p_{elevated} max. pressure with elevated arms in [bar].

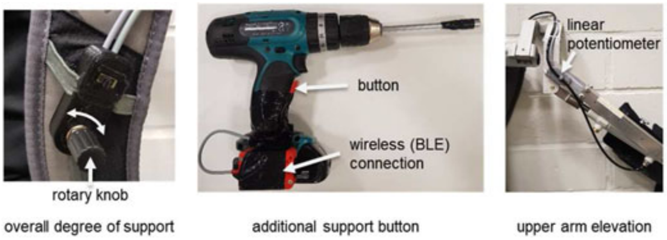

Fig. 4. Overall degree of support (adjusted by rotary knob), elevation of upper arm and support button state are used to create reference pressure for the low-level pressure control loop of $p_{support}$, pneumatic valves are connected to supply pressure p_{supply} from reservoir and vent to the atmosphere (p_{atm}).

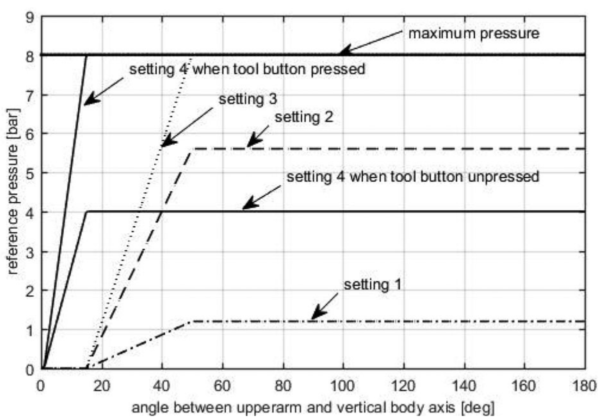

Fig. 5. Reference pressure over arm elevation for different test cases. Pressure is reduced, when arms are lowered and linearly increases with arm elevation. Switch button doubles pressure in test case 4.

$p_{s_{\text{ref}}}$ is reduced to zero when the upper arm elevation is smaller than a minimum elevation angle α_{start} and rises linearly until α_{end} to the maximum value given by p_{elevated} according to (2).

The maximum pressure with elevated arms

$$p_{\text{elevated}} = \eta_{\text{selected}} \cdot p_{\text{max}} \tag{3}$$

with:

- η_{selected} selected amount of support [0-1] as well as
- p_{max} maximum pressure in $\text{N} \cdot \text{m}^{-2} = 8$ [bar].

is calculated based on η_{selected} and the supply pressure p_{max} according to (3). If no tool is connected, the rotary knob at the shoulder strap can change the value of η_{selected} between zero and one. If a tool is connected and the button at the tool grip (Fig. 3(b)) is not pressed, η_{selected} is reduced to the half. Pressing the tool button is then necessary to receive the full support pressure.

The linear increase of pressure (see Fig. 5 for exemplary curves) according to (2) results in a more than linear increase of torque (see Fig. 6 for exemplary torque profiles) given the characteristics of the actuator kinematic defined by (1).

IV. Evaluation of Subjective Performance and Movement Velocity

The active support comes at the cost of a substantially more complex system and necessitates a clear evaluation whether or not the additional effort is justified. Four test cases have been replicated in the laboratory in order to assess how the active

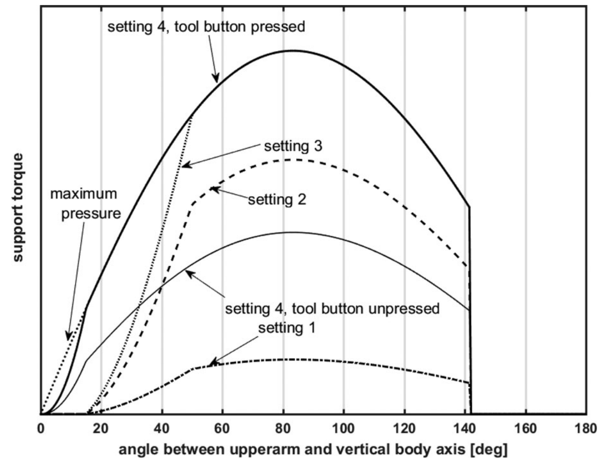

Fig. 6. Torque τ generated in the different experimental test cases with the pressure profiles from Fig. 5 and (1).

TABLE I
Experimental Test Cases

Test case	Settings of pressure calculation			Objective
	α_{starts}	α_{end}	η_{selected}	
1	15°	50°	0.15	minimal support – baseline
2	15°	50°	0.7	medium support test
3	15°	50°	1.0	maximum support test
4	1°	15°	0.5/1.0	adaptive support test

exoskeleton Lucy performs in three different scenarios. Key questions for the evaluation were:

- Is an active exoskeleton necessary or is a passive one performing similarly well?
- Is the support system Lucy capable of generating a substantial support?
- How well does the proposed user interface allow to adjust the support force during different working tasks?

A. Experimental Setup

To evaluate the effect of Lucy 2.0 eight test subjects performed three tasks under four different parameters (test cases). Three qualitative variables and one quantitative variable were observed.

1) Parameter Settings in Test Cases: In test case $\{1\}$ pressure reference η_{selected} was set to 0.15 (15% of maximum pressure), such that the arm rest moves freely with the arms without generating substantial support (see Table I). In test cases $\{2\}$ η_{selected} was set to 0.7 and to 1.0 in test case $\{3\}$ in order to assess the overall performance of Lucy 2.0 in a configuration, which represents that of an elaborate passive exoskeleton. The fourth test case comprises two values for η_{selected}. By pressing a button mounted to the grip of the tools users were able to set η_{selected} to 1.0. Upon release, it was reset to 0.5. Whereas test case 4 might seem rather specific, as it requires a tool to be used, it serves to evaluate the effect of an adaptive active exoskeleton, as the effect of pressing a button can be generalized to an intelligent top level control structure evaluating multiple types of sensor data.

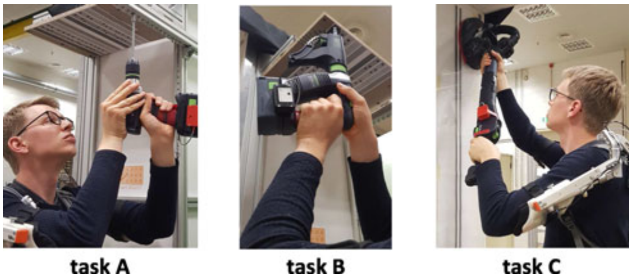

Fig. 7. Tasks performed by test subjects setting metal screws on the ceiling setting screws from screw belt on the ceiling, as well as grinding walls.

B. Description of Experimental Work Tasks

The study uses tasks derived from real applications. Tasks are carried out in various body positions and orientations as well as with different tools and thus different actions. The tasks are illustrated in Fig. 7 and described in the following.

Task A – "fastening object above head level"

Task A is a highly dynamic task based upon task profiles in automobile manufacturing and industrial applications. This task is characterized by the change between a light object (100 g) and a heavy tool (2,000 g). For the study, 15 repetitions of 25 second duration with three seconds break are to be executed. Task A comprises three steps:

- take lightweight paper box out bigger paper box 50 cm away,
- turn around 180° and put paper box on shelf about 30 cm above head level, as well as
- take drill and fasten five screws about 30 cm above head level.

Task B – "setting screws above head level"

Task B is a strenuous dynamic task based on a typical activity in construction industry – screwing on the ceiling in context of drywall construction – with the possibility to lower arms completely between repetitions. Within the scope of this task, a tool with a weight of 2,000 g has to be handled. In addition, a vertical processing force of 50 N has to be applied. The task consists of 30 repetitions of six second duration with about three seconds break. Two main steps are necessary:

- raise arms and position tool tip to either of two markers on wall mounted about 30 cm above head level, as well as
- press tool (automatic drywall drill) against wall until tool starts drilling.

Task C – "grinding at the wall"

Task C is a medium dynamic task with a heavy tool and no possibility to relax muscles between repetitions based on a task from construction industry – grinding of walls. The task C consists of 20 repetitions of five seconds. Two steps are necessary:

- move long-neck sander 1.2 m up from horizontal position wait for acoustic signal ("beep"), as well as
- move grinder slowly down and wait for next acoustic signal.

C. Observed Variables

To assess the perceived performance of the exoskeleton after each run of the three tasks the subjects were asked to give three qualitative parameters:

TABLE II
QUALITATIVE RESULTS FOR TASK A

Test case	Perceived task effort–Borg CR10		User support rating: −3 (too low) to +3 (too strong)		Push down force: 0 (no force) to 6 (strong force req.)	
	M	SD	M	SD	M	SD
1	4.3	1.03	−2.9	0.35	0.0	0.00
2	2.3	1.03	−0.2	0.75	1.7	0.88
3	2.4*	2.13	1.8**	1.00	3.6**	1.19
4	1.6*	0.86	0.1	0.56	0.5***	1.07

M: mean SD: standard deviation.
*significant reduction over test case 1 (Friedman test, $p < 0.05$).
**significant increase over test case 1 (Friedman test, $p < 0.05$).
***significant reduction over test case 3 (Friedman test, $p < 0.05$).

1. rating of perceived exertion (Borg CR10 [21]: 0 = no effort – 10 = maximum effort),
2. rating of perceived strength of support force ($\{-3\}$ = too low – $\{0\}$ = about right – $\{+3\}$ = too strong) as well as
3. perceived force needed to lower arm ($\{0\}$ = no force necessary – $\{6\}$ = strong force necessary).

Besides these three qualitative parameters, the angular position α of the upper arm sensor was evaluated ($f_{\text{sample}} = 10$ Hz).

D. Statistical Analysis

A statistical analysis was conducted using SPSS ver.22 (IBM statistics Armonk, NY, United States) to test if a) perceived task effort (Borg CR10), b) user support rating and c) perceived force to lower the arm differ between test cases. Furthermore, the means of positive and negative velocities for all test cases were compared. Significance was set at $\alpha = 0.05$. A Kolmogorov-Smirnov test revealed a non-normal distribution. Therefore, a non-parametric Friedman test of differences among repeated measures was conducted. Bonferroni post hoc test were applied to significant differences.

Due to technical issues, angular velocities of left and right active joints were derived from angular position values for only six test subjects. Mean negative/positive velocity were calculated as the mean value of velocity values with either negative/positive sign. A difference between positive and negative values has been made in order to differentiate between the upwards movement, which is supported by the system and the downwards movement, where the user has to work against the system. Velocity values with an amount of less than 20°/s have been discarded, in order to discard times of slow motion (especially resting time).

E. Results

1) Task A: The qualitative questionnaires showed significant differences between test cases (Borg scale: $\chi^2(3) = 14.620$, $p = 0.002$; user support rating: $\chi^2(3) = 22.066$, $p < 0.001$; perceived push down force: $\chi^2(3) = 21.169$, $p < 0.001$). Post hoc tests showed significant differences for Borg scale between test cases $\{1\}$ and $\{3, p = 0.006\}$ as well as $\{4, p = 0.022\}$. For user support rating a significant difference was found between $\{1\}$ and $\{3, p < 0.001\}$ (see Table II).

There were significant differences for perceived push down force between $\{1\}$ and $\{3, p < 0.001\}$ and between $\{3\}$ and $\{4, p = 0.004\}$ which means the perceived force to push the

TABLE III
QUALITATIVE RESULTS FOR TASK B

Test case	Perceived task effort – Borg CR10		User support rating: −3 (too low) to +3 (too strong)		Push down force: 0 (no force) to 6 (strong force req.)	
	M	SD	M	SD	M	SD
1	5.6	1.19	−2.9	0.35	0.0	0.00
2	3.3	1.75	−1.1	0.83	0.8	1.04
3	2.6*	0.74	−0.2**	0.53	1.6**	1.60
4	2.2*	1.13	−0.4**	0.52	0.8	1.20

M: mean SD: standard deviation.
*significant reduction over test case 1 (Friedman test, $p < 0.05$).
**significant increase over test case 1 (Friedman test, $p < 0.05$).

TABLE IV
QUALITATIVE RESULTS FOR TASK C

Test case	Perceived task effort–Borg CR10		User support rating: −3 (too low) to +3 (too strong)		Push down force: 0 (no force) to 6 (strong force req.)	
	M	SD	M	SD	M	SD
1	6.3	1.83	−3.0	0.00	0.0	0.00
2	3.7	1.53	−0.8**	1.56	0.6	1.06
3	2.9*	1.36	−0.2**	1.33	1.2	1.56
4	3.2*	1.41	−0.8**	0.65	0.7	1.33

M: mean SD: standard deviation.
*significant reduction over test case 1 (Friedman test, $p < 0.05$).
**significant increase over test case 1 (Friedman test, $p < 0.05$).

exoskeleton down is significantly lower when the push button is activated in test case {4} when compared to test case {3}. For the positive velocity there was found to be a significant difference between test cases (right arm: $\chi^2(3) = 11.400$, $p = 0.010$; left arm: $\chi^2(3) = 9.400$, $p = 0.024$).

Post hoc tests showed significant differences between test cases {1} and {2} (right arm: $p = 0.005$ and left arm: $p = 0.022$) (see Table VI). For negative velocity no significant differences were found.

2) Task B: The qualitative questionnaires showed significant differences between test cases (Borg scale: $\chi^2(3) = 16.671$, $p = 0.001$; user support rating: $\chi^2(3) = 19.208$, $p < 0.001$; perceived push down force: $\chi^2(3) = 12.529$, $p = 0.006$).

Post hoc tests showed significant differences for Borg scale between test cases {1} and {3, $p = 0.002$} as well as {4, $p = 0.002$}. For user support rating a significant difference was found between {1} and {3, $p < 0.001$} as well as between {1} and {4, $p = 0.006$}. There were significant differences for perceived push down force between {1} and {3, $p < 0.030$} (see Table III).

No significant differences for either positive or negative velocity can be reported for task B (see Table VII).

3) Task C: The qualitative questionnaires showed significant differences between test cases (Borg scale: $\chi^2(3) = 14.292$, $p = 0.003$ and user support rating: $\chi^2(3) = 15.846$ $p = 0.001$). No significant differences were found for perceived push down force. Post hoc tests showed significant differences for Borg scale between test cases {1} and {3, $p = 0.008$} as well as {4, $p = 0,016$}. For user support rating a significant difference was found between {1} and {2, $p < 0.040$}, between {1} and {3, $p = 0.001$} as well as between {1} and {4, $p = 0.022$} (see Table IV).

For the positive velocity there was found to be a significant difference between the test cases (right arm: $\chi^2(3) = 8.000$, $p = 0.046$; left arm: $\chi^2(3) = 14.600$, $p = 0.002$).

Post hoc tests showed significant differences for the right arm between test cases {1} and {3, $p = 0.044$} and for the left arm between {1} and {3, $p = 0.010$} as well as between {1} and {4, $p = 0.005$} (see Table VIII). For negative velocity a significant difference for the right arm was found ($\chi^2(3) = 10.400$, $p = 0.015$) between test cases {1} and {3, $p = 0.44$}.

V. EVALUATION OF MUSCLE ACTIVITY

To obtain more detailed information about the effect on muscle activity, a further investigation using surface electromyography was performed and will be presented here.

A. Experimental Setup

The experimental setup was similar to the setup used in the previous chapter. However, due to the effort required to perform these measurements, only three test subjects have been measured and the experiment was limited to a single task. The three test subjects (two male, one female, height: 1.84 m ± 0.10 m; weight: 86.3 kg ± 5.5 kg; age: 32.6 years ± 8.9 years) performed task A with Lucy in settings {3} and {4} from the previous chapter and without Lucy. Task A represents the application where the active support mode using the button at the tool grip is most relevant.

B. Observed Muscles and Measurement Protocol

The activity of the front shoulder muscles (anterior deltoid) on both left and right side of the body was tracked using surface electromyography (myon AG, CH) at 1,000 Hz using standard SENIAM procedure [22]. This muscle is considered to contribute the most in holding/moving the arm into an upward position (anteversion). Additionally, its antagonist, latissimus dorsi (a large flat muscle on the back) was also measured on both left and right side to evaluate the effort necessary to move the arm down (retroversion) against resistance from the exoskeleton. The raw data was collected and later filtered digitally using the software ProEMG (myon AG) with a 20–200 Hz 2nd order butterworth bandpass filter. A time period of 100 ms was used to determine RMS. In order to normalize the amplitudes of the EMG to a reference, EMG-data was normalized relative to the maximum voluntary contraction (MVC) values which were assessed prior to the actual measurement.

C. Statistical Analysis

For each test subject 15 assessed work cycles (25 second duration per cycle) in each mode have been time normalized and the means of the muscle activity for each mode have been calculated. Due to the small sample size, intra-individual changes in muscle activity are being reported, rather than statistical comparisons of the means between subjects.

D. Results

As it can be seen in Table V muscle activity of the anterior deltoid muscle has been reduced by the use of Lucy for

TABLE V
MUSCLE ACTIVITY FOR TASK A

Subject	Drill hand	Muscle	Average muscle activity [% MVC]			Change of muscle activity rel. to baseline condition	
	right/left		baseline – without Lucy	with Lucy - "button INACTIVE" – setting {3}	with Lucy – "button ACTIVE" –setting {4}	"button inactive" setting {3}"	"button active" setting {4}
1	right	deltoid left	21.3 ± 8.1	10.2 ± 4.8	13.0 ± 5.8	−52.2%	−39.1%
		deltoid right	21.7 ± 9.6	9.1 ± 5.0	11.0 ± 4.4	−58.2%	−49.3%
		lat. dor. left	4.8 ± 1.0	4.0 ± 1.4	3.5 ± 0.7	−15.0%	−26.8%
		lat. dor. right	8.5± 2.0	8.7 ± 4.8	2.0 ± 0.9	+2.2%	−75.8%
2	right	deltoid left	29.4 ± 16.6	19.7 ± 14.9	21.0 ± 14.5	−32.8%	−28.6%
		deltoid right	25.4 ± 13.6	18.6 ± 13.4	16.3 ± 11.4	−26.5%	−35.5%
		lat. dor. left	5.2 ± 1.9	3.0 ± 1.1	3.6 ± 1.6	−41.5%	−31.0%
		lat. dor. right	6.6 ± 2.9	6.9 ± 4.2	8.3 ± 5.0	+4.8%	+26.4%
3	left	deltoid left	18.7 ± 11.50	13.4 ± 8.9	16.20 ± 10.4	−28.3%	−13.6%
		deltoid right	23.8 ± 13.5	15.3 ± 10.3	19.9 ± 12.2	−35.6%	−16.5%
		lat. dor. left	11.0 ± 4.4	6.4 ± 1.7	6,.8 ± 2.0	−41.7%	−38.5%
		lat. dor. right	7.0 ± 2.3	5.2 ± 1.3	5.5 ± 1.9	−26.2%	−21.8%

TABLE VI
VELOCITIES OF UPPER ARM

Test case	positive velocity (°/s)				negative velocity (°/s)			
	left		right		left		right	
	M	SD	M	SD	M	SD	M	SD
1	84.2	10.7	90.4	6.7	−96.5	18.9	−94.6	5.4
2	98.6*	13.8	99.9*	12.1	−99.8	15.1	−90.6	7
3	92.9	13.7	99.1	16.6	−95.1	18.5	−89.9	12.5
4	95.2	15.1	97.8	12.2	−103.5	21.9	−93.7	6.9

M: mean SD: standard deviation.
*significant increase of vel. over test case 1 (Friedman test, $p < 0.05$).

TABLE VII
VELOCITIES OF UPPER ARM

Test case	Positive velocity (°/s)				Negative velocity (°/s)			
	left		right		left		right	
	M	SD	M	SD	M	SD	M	SD
1	73.7	16.9	66.8	14	−95.8	29.1	−80.3	17
2	80.2	22.6	80.4	20.3	−94.2	34	−79.8	22.9
3	81.5	19.9	79.7	20.2	−89.6	26.8	−74	18.5
4	81.7	21.6	82	18.2	−97.5	31.2	−83.6	22.9

M: mean SD: standard deviation.

TABLE VIII
VELOCITIES OF UPPER ARM

Test case	Positive velocity (°/s)				Negative velocity (°/s)			
	left		right		left		right	
	M	SD	M	SD	M	SD	M	SD
1	34.3	6.1	73.3	14	−33	5.2	−67.2	11.2
2	40.1	5.9	73.4	15.3	−33.8	7.5	−59	12.1
3	44.6*	4.8	84.4*	13.9	−35.3	4.9	−60.4	8.7
4	45.8*	6.5	80.2	15.3	−40	4.9	−65.7*	13.1

M: mean SD: standard deviation.
*significant increase of vel. over test case 1 (Friedman test, $p < 0.05$).

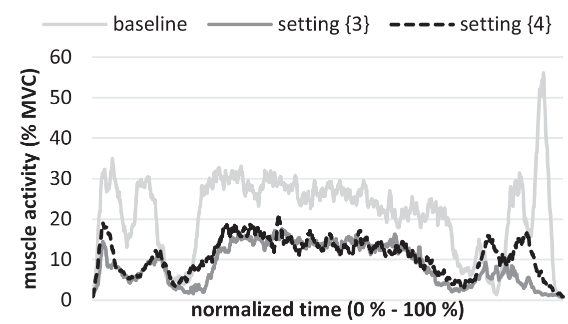

Fig. 8. Exemplary EMG signal for the deltoid right of one test subject.

all test subjects and with both control settings relative to the baseline condition without Lucy. Reduction lies in the range of −26.5% to −58.2% for the control setting {3} and in the range of −13.6 % to −49.3% for test case {4}. The activity of latissimus dorsi has been reduced by the use of Lucy in most cases. However, for test subject one and two there was a slight increase on the right side (+2.2/4.8%) for control setting {3} and a moderate increase (+26.4%) for subject two with control setting {4} activated. An exemplary EMG signal is illustrated in Fig. 8.

VI. DISCUSSION

Results from the evaluation in the laboratory show, that Lucy 2.0 is generally capable of generating a substantial amount of support. EMG measurements demonstrate, that muscle activity can be reduced and qualitative parameters show, that the overall task effort can be reduced as well by using the proposed pneumatic exoskeleton.

When the button at the tool grip was activated during task A, perceived resistance to move the arm down is significantly lower, whereas perceived task effort was lower or not noticeably higher. This shows, that using a button at the tool grip can be a viable method, to adjust the support force of the system during the work process and without the practical limitations of EMG. However, that the effect size is lower for task B and C when compared to task A, shows, that probably not all applications need an active exoskeleton with an intensive set of sensors, actuators and electronics. Besides, several users reported to prefer test case {4}, as it gave them the feeling of control over the exoskeleton, which is in the end essential for user acceptance. Further analysis will therefore focus on these perceived soft factors as well.

Positive upper arm velocities measured via the exoskeleton sensors are generally higher for the supported modes {2, 3, 4} over mode {1}, indicating a potential positive influence on productivity. As this difference is however only significant in some test cases/tasks, it needs to be further investigated.

As for the reasons why latissimus dorsi showed a reduced activity whilst wearing Lucy although the test subjects had to work against a certain amount of resistance for the retroversion, we assume that the provided support not only reduced necessary muscle activity for anterior deltoid but also reduced the need for joint stabilization by the latissimus dorsi during anteversion. Further research is needed to validate this hypothesis.

VII. Conclusion

This study serves as a basis for further technical development in the area of actuation and control for industrial exoskeletons. One key goal of the study was to evaluate what features are necessary to control the exoskeleton and when getting active support power for which kind of activities is necessary. In respect to this aspect, it has successfully been shown, that especially for tasks with varying load, active support is greatly beneficial. The generally positive feedback of the actively controlled test case {4} is motivation to develop more advanced means of input and intensify research on the interaction between tool, user and support system.

Next steps will also need to include more detailed biomechanical analysis, in order to assess the effects on muscle activity and movement of not only the upper arm, but also the rest of the body.

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